



Dependence of temperature sensitivity of soil organic carbon decomposition on nutrient management options under conservation agriculture in a sub-tropical Inceptisol



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ABSTRACT

Assessment of temperature sensitivity of soil organic carbon (SOC) mineralization from soils of long-term precision conservation agriculture (CA) plots is essential to forecast soil C dynamics. Under CA, varying quantity of inorganic nutrient application had differential impact on SOC. At the same time study of SOC mineralization at different simulated temperatures is important as global climate change affects C-cycle of an agro-ecosystem. To assess the impact of tillage and nutrient management on SOC build-up, a long-term study (five year old) with 3-tillage practices [ZT-zero tillage; PB-permanent beds, & CT-conventional tillage] in main plot and 4-nutrient management strategies [unfertilized, farmer fertilizer practice-FFP, recommended fertilizers-Ad-hoc and a site specific nutrient management-SSNM] in sub-plot in a maize-wheat-mungbean system was chosen. To measure the build-up and thermal sensitivity of SOC, soil samples from 3- depths (0–7.5, 7.5–15 and 15–30 cm) were collected. The kinetics of C-mineralisation was studied through laboratory incubation at 3-temperatures (27, 32 and 37 °C) for 90 days. The PB/ZT and SSNM had significantly higher SOC compared with CT and unfertilized plots, respectively. Although the cumulative C mineralization after 90-days of incubation followed the trend of SOC content among the treatments, while decay rates of SOC mineralization showed somewhat different trend. In all the tillage treatments the percentage of SOC mineralised ranged between 3.3–5.8% at 27 °C, 5.2–8.1% at 32 °C and 7.3–10.9% at 37 °C. At higher temperature, higher SOC decay rates were observed under CT and unfertilized plots compared with PB/ZT and SSNM plots, respectively. The SOC from lower soil depth in CT and unfertilized plots was more temperature sensitive ($Q_{10} = 4.03$ and 4.89, respectively) compared to those under CA-based PB/ZT ($Q_{10} = 2.63$ –2.82) and SSNM ($Q_{10} = 2.15$) based balanced nutrition, respectively. The SOC in lower soil depth (7.5–15 and 15–30 cm) is 1.3 and 2.1 times more temperature sensitive respectively than surface soil depth of 0–7.5 cm soil depth. Higher proportion of less labile SOC under CT and unfertilized plots might be the reason for higher temperature sensitivity. In the inevitable and impending global climate change scenario, we might lose a sizeable amount of sequestered C, which is otherwise stable at present ambient temperature.

1. Introduction

Soil organic carbon (SOC) is a vital and dynamic part of global carbon stock (Raich and Schlesinger, 1992; Kirschbaum, 1995).

Naturally carbon exchanges between terrestrial eco-system and the surrounding atmosphere by means of various biotic and abiotic processes. Respiration and photosynthesis, decomposition, mineralisation and immobilization and combustion, altogether constitute the carbon

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cycle. Soil carbon pools are diminishing with increasing human intervention and concurrently atmospheric CO₂ concentration is increasing (IPCC, 2013). Prevailing environmental conditions (temperature and precipitation), plant derived carbon inputs *i.e.* plant leachates, root exudates, and litters, residues and fragmented plant structures, and outputs as heterotrophic microbial respiration (*i.e.* mineralization) determine the SOC pool (Kundu et al., 2007). A noteworthy loss of carbon from soil to atmosphere is an important aspect of climate change and food security, as it simultaneously declines the soil quality and increases the atmospheric CO₂ concentration. Factors which affect the activities of organic matter decomposers communities, impacts C mineralization. For instance, the role of temperature and soil moisture is well recognized on microbial population for SOC decomposition (Kirschbaum, 2004). Soil microbial diversity (Lange and Green, 2005), as well as the quantity and quality of available substrate (Yang et al., 2009), affects SOC mineralization. The climate change may alter the kinetics of C mineralization (IPCC, 2013) as the warming of atmosphere acts as a positive feedback for climate change by accelerated decomposition of SOC stock with enhanced microbial respiration and henceforth more release of soil carbon to atmosphere (Davidson and Janssens, 2006). Favourable impact of rising temperature for superior microbial activity and SOC turnover is a widely established fact. Exposure of soils to high temperatures in tropical regions results in faster soil organic matter (SOM) decomposition with more C release to atmosphere (Li et al., 2015). The released CO₂ being a greenhouse gas has role in increasing global temperature. Average increase in soil respiration was about 20% by elevating soil temperature by 0.3–6.0 °C (average 2.4 °C) in soil-warming experiments carried out worldwide, having a Q₁₀ of about 2.1 (Rustad et al., 2001).

Temperature sensitivity, usually indicated by Q₁₀ represent the increase in the decomposition rate of SOC with increase of the temperature by 10 °C (Fang and Moncrieff, 2001). Findings of other studies showed that Q₁₀ values varied largely across the range of temperatures (Ghosh et al., 2016, 2018b). Regarding temperature sensitivity of pools of SOC, researchers have contrasting opinions. Some studies found insensitiveness of recalcitrant C to varying temperature (Giardina and Ryan, 2000), whereas, some reported that non-labile pool is more sensitive than labile pool (Fierer et al., 2005; Knorr et al., 2005). On the other hand, there were reports of similar temperature sensitivity of labile and non-labile SOC (Conen et al., 2006; Fang et al., 2005). Understanding the temperature sensitivity of SOC decomposition will acknowledge the practices, which favour soil C dynamics towards SOC build-up.

Reduced organic C addition and repetitive soil disturbance, coupled with changing climatic condition are not congenial for SOC build-up in the tropics (Brown and Lugo, 1994; Singh-Brar et al., 2015). Monocropping and residue removal leads to declining SOC content and poor soil aggregate stability and causes soil health deterioration (Marinari et al., 2010; Raiesi, 2006). Based on the principle of minimum soil disturbance, organic cover on the soil surface and diversified cropping system, Conservation agriculture (CA) is a set of crop production practice improving soil health, yield level and environmental quality (Jat et al., 2012; Kassam et al., 2009; Parihar et al., 2016a). Positive changes in SOC content have been reported with adoption of CA practices in different cropping systems under varied agro-ecological conditions (Chivenge et al., 2007; Choudhary et al., 2018; Parihar et al., 2018). Annual addition of organic matter and plant-derived carbon inputs to soils must exceed decomposition to stabilize SOC. Application of optimum and balanced dose of nutrients are beneficial for the crop growth (Parihar et al., 2017a, 2017b) and hence can increase SOC stock. Aula et al. (2016) had observed significant effect of N doses on SOC stock. It is well known that increased vegetative growth with N application increases the root growth, root exudates and in turn the C returned to the soil. Long-term application of inorganic fertilizers along with organic manures increases the total SOC and its' pools (Xu and Saier, 2010). Adoption of CA improves SOC stock, and maintains long-

term sustainability of agro ecosystems productivity under climate change scenarios due to its favourable impact on soil health (Tian et al., 2016).

With the adoption of CA practice in maize–wheat–mungbean (MWMb) rotation, it is becoming popular among farmers of Indo Gangetic plains (IGP) region where previously RW system was dominating. Permanent bed (PB) planting increases the crop performance with a co-benefit of improved soil and environment quality (Lichter et al., 2008). The PB and ZT planting, and crop residue retention along with balanced fertilizer application leads to enhanced production and recycling of biomass through a favourable alterations in soil physical, chemical and biological properties (Jemai et al., 2013; Parihar et al., 2016a, 2016b). Although the biomass recycling increases the SOC content worldwide (Saharawat et al., 2010), its temperature sensitivity under different tillage, residue and nutrient management options in a sub-tropical agro-ecosystem is unknown.

Keeping an insight on increasing global mean temperature, and improved SOC content and its' pools in different CA-based management options, an excellent prospect is to study the SOC mineralization at graded temperature *i.e.*, SOC mineralization-temperature sensitivity relationship. With expected increase in mean temperature and observable improvement in soil health, we explored the impact of graded temperature (27, 32 and 37 °C) on SOC decomposition, changes in SOC pools based on equivalent soil mass approach under a medium-term study in CA-based cropping system, as affected by tillage, residue and nutrient management. The hypotheses of the study were: (i) the CA-based tillage and residue management, and SSNM-based nutrient management protocols would have significant improvements in SOC, and; (ii) the temperature sensitivity of SOC mineralization will be differentially impacted by CA-based PB/ZT and SSNM practices compared with other tillage, residue and nutrient management practices. The objective of this study were: (i) to evaluate the differential effect of tillage, residue and nutrient management options on total SOC and its pools, and (ii) to study the effect of different tillage, residue and nutrient management practices on temperature sensitivity of SOC decomposition.

2. Materials and methods

2.1. Experimental site and design

To fulfil the above mentioned objectives, an on-going experiment on CA at the research farm of Indian Institute of Maize Research (IIMR), New Delhi, India situated in north-western IGP was chosen as test site. The site has a sub-tropical climate with hot and dry summers, and cold winters. The average annual rainfall of the site is ~652 mm. The experimental plot was situated at 28°38'N latitude, 77°11'E longitude, and 228.6 m altitude. The initial properties of the experimental soil referred it as a very deep (> 2 m), flat, well-drained, non-saline soil (EC 0.32 dS m⁻¹) with an alkaline reaction (pH = 7.9) and sandy loam texture (Table 1). A maize-wheat-mungbean (MWMb) rotation was being followed since the commencement of the trial in 2012. The experiment was laid out in a split-plot design and replicated thrice. In the main plots, there were 3-treatments involving tillage and residue management [ZT: Zero tillage with residue retention of previous crop; PB: Permanent bed with residue retention of previous crop; and CT: Conventional tillage with residue incorporation of previous crop], whereas in the sub-plots there were 4-treatments involving nutrient management protocols [Unfertilized: control; FFP: typical farmers' fertilizer practice with N:P:K @ 110.0:13.2:0.0 and 172.0:25.3:0.0 kg ha⁻¹ in maize and wheat, respectively; Ad-hoc: Indian Council of Agricultural Research (ICAR) recommended fertilizers dose (Ad-hoc) with N:P:K @ 150.0:26.2:33.3 and 120.0:26.2:33.3 kg ha⁻¹ in maize and wheat, respectively; and Nutrient Expert® decision support tool-based fertilizer application (Pampolino et al., 2012) which represented site specific nutrient management (SSNM) with N: P₂O₅: K₂O @ 167:32:38

Table 1
Initial soil properties and climatic parameters of the experimental site.

A. Climatic parameters	Mean of 33 years prior to experimentation	Mean of 5 year (2012–2017) of study period
Maximum temperature (°C)	31.0	31.0
Minimum temperature (°C)	17.6	17.3
Rainfall (mm)	707.4	1026.8
B. Soil parameters		
Taxonomical classification	Typic Haplustept	
Texture	Sandy loam	
Sand (%)	64.1	
Silt (%)	16.9	
Clay (%)	19.0	
pH	7.9	
EC (dS m ⁻¹)	0.32	

and 144:56:58 kg ha⁻¹ in maize and wheat, respectively]. The total area of each experimental unit was 4.02 m × 7.5 m.

2.2. Soil and crop management

Prior to establishment of the trial, the site was deep-tilled and laser-levelled. The CT planting consisted of one deep tillage using a disc harrow, followed by spring-tine cultivator and rotavator. The ZT planting was done through ZT planter resulting in direct drilling of crop seeds in soil. Raised beds were developed by bed/ridge former in the first season of experimentation itself, and maintained as permanent beds (PB) for succeeding seasons, with re-shaping of beds once annually. The seeds were planted on PB using a raised bed multi-crop planter. In all the plots, 30% (maize and wheat) and 100 % (mungbean) residues were retained (in ZT and PB) /incorporated (in CT) in the subsequent crops.

2.3. Collection and processing of samples

After completion of 5-cropping cycles, composite soil samples were collected from 0–7.5, 7.5–15 and 15–30 cm layers using a tube auger of 7 cm diameter, and stored moist in polyethylene bags at 4 °C until used for analysis. A set of sub-samples were taken out and air-dried, ground in a wooden mortar and pestle, and sieved to pass through a 0.2 mm sieve, for analysis of different C pools. The rest of samples stored in refrigerator were used to set up an incubation study to measure C mineralization.

2.4. Different soil organic carbon pools of varying lability

The processed soil samples were used for total C determination using a CHN analyser (EuroVector Instruments, EA 3000, Italy). Total soil inorganic C (SIC) was measured titrimetrically by digesting the soil with dilute HCl and then back titrating the excess HCl with dilute NaOH (Richards, 1954; Jackson and Barak, 1967). Per cent CaCO₃ present in soil can be measured through the above mentioned titration using following formula.

$$\text{CaCO}_3 (\%) = (S - T) \times N \times 5/W$$

where, T = Volume of 0.5 N HCl consumed in sample titration; S = Volume of 0.5 N HCl volume consumed in blank titration; W = sample weight, g; N = HCl normality. From the amount of CaCO₃, the total SIC was calculated (Gupta et al., 2014; Dey et al., 2016; Ghosh et al., 2016, 2018a, 2018b). Total soil organic carbon (SOC) concentrations were then computed subtracting total SIC from total C concentrations.

Different pools of SOC with varying lability were estimated following Walkley and Black (1934) method as modified by Chan et al. (2001) using 5, 10, and 20 mL concentrated (18 mol L⁻¹) H₂SO₄ and K₂Cr₂O₇ solution. This resulted in three acid-aqueous solution ratios of 0.5:1, 1:1, and 2:1 corresponding to 12, 18, and 24 N H₂SO₄,

respectively, and caused production of different amounts of heat of reaction for SOC oxidation. The amounts of C thus determined, allowed separation of total SOC into the following four pools of decreasing oxidizability:

Very labile SOC (VLSOC): Organic C oxidisable under 12 N H₂SO₄

Labile SOC (LSOC): The difference in organic C oxidisable under 18 N and that under 12 N H₂SO₄

Less labile SOC (LLSOC): The difference in organic C oxidisable under 24 N and that under 18 N H₂SO₄

(24 N H₂SO₄ is equivalent to the standard Walkley and Black method)

Non-labile SOC (NLSOC): The difference in total SOC and organic C oxidisable under 24 N H₂SO₄.

Carbon management index (CMI) was calculated using the following equations (Blair et al., 1995) using reference soil sample.

$$\text{Lability of SOC (L)} = (\text{VLSOC} + \text{LSOC} + \text{LLSOC})/\text{NLSOC}$$

$$\text{Carbon Pool Index (CPI)} = \text{Sample total SOC}/\text{Initial total SOC}$$

$$\text{Lability Index of C (LI)} = \text{Lability of SOC in sample soil}/\text{Lability of SOC in Initial soil}$$

$$\text{Carbon management index (CMI)} = \text{CPI} \times \text{LI} \times 100$$

2.5. Soil incubation study

Laboratory incubation was carried to find the C mineralization for each of the treatment combination of the tillage and nutrient management. Soil samples from 3 depths (0–7.5, 7.5–15 and 15–30 cm) was incubated for 90 days in three temperature of 27, 32 and 37 °C, corresponding to the temperature of winter, rainy and summer season respectively. Moisture content of all the collected soil samples was measured gravimetrically by taking a small amount of soil. Before placing the soil in incubation jar moisture content was adjusted to field capacity and paraffin wax was applied at the edges. A 100 g soil sample from each depth and subplot of experiment was taken in glass jar of 500 mL volume for each temperature in three replicates along with blank jar without soil. An alkali trap containing 20 mL NaOH (0.5 N) was hanged with thread inside every incubation jar. The contents of alkali trap was titrated with 0.5 N HCl at pH 8.3 in the presence of BaCl₂, periodically after 3, 7, 15, 22, 30, 45, 60, and 90 days of incubation, to obtain cumulative SOC mineralization in the specified interval. After each removal of alkali trap, air was passed into incubation flasks for optimum O₂ supply. Ambient soil moisture was also measured in each sampling dates and calculated amount of water was added to maintain field capacity.

The equation used for CO₂ flux measurement is given below:

$$\text{CO}_2\text{-C evolved (mg kg}^{-1}\text{)} = (A - B) \times N \times 6$$

Where A and B are the volume (mL) of HCl consumed for titrating 20 mL 0.5 N NaOH in control (without soil) and soil, respectively, N is the

normality of HCl, and 6 is the equivalent weight of C.

The data was fitted in exponential model to obtain kinetics of SOC mineralization (Stanford and Smith, 1972).

$$C_t = C_0 (1 - e^{-kct})$$

Where, C_0 represents the potentially mineralizable carbon and C_t is the pool of C mineralized at time t , with decay rate K_c .

An exponential function was used to fit SOC decomposition rates with incubation temperatures

$$K_T = R_0 e^{bT}$$

Where K_T is the rate of CO_2 -C evolution (soil respiration rate) at T° C temperature, R_0 is the soil respiration rate at 0° C temperature and b is temperature coefficient.

The temperature sensitivity (Q_{10}) of SOC was estimated using the following equation

$$Q_{10} = e^{10b}$$

2.6. Statistical analysis

Data were subjected to analysis of variance (ANOVA) using the general linear model procedures of the statistical analysis system (SAS Institute, Cary, NC) for split-plot design (Gomez and Gomez, 1984) using SAS 9.3 software. The least significant difference test was used to decipher the effects of treatments at 5% level of significance.

3. Results

3.1. Soil organic carbon and its' pools

Five years of nutrient, tillage and residue management had astonishing effect on total SOC as well as its different pools of varying lability (Table 2). Maximum SOC resided in the non-labile pool, across the depth in all the treatments. The percentage distribution of SOC in different pools i.e., VLSOC, LSOC, LLSOC and NLSOC were 22, 15, 22 and 41%, respectively, in the surface 0–7.5 cm soil layer. On the other hand, in lower depths, like in 15–30 cm layer, the VLSOC (9%) and LSOC (12%) decreased with a simultaneous increase in LLSOC (36%) and NLSOC (43%).

The CA-based PB and ZT treatments registered significantly higher total SOC concentration by 24.8 and 22.1% in 0–7.5 cm, 20.5 and 22.0% in 7.5–15 cm and 15.3 and 19.1% in 15–30 cm compared with respective soil layers under CT (Table 2). On the other hand, the nutrient management options i.e. SSNM and *Ad-hoc* recorded significantly higher total SOC concentration compared with FFP plots, the increments being 21.3–27.8% and 18.2–25.3%, respectively across the soil

layers. The treatments FFP had similar concentrations of total SOC compared with unfertilized (control) treatment in all soil depths studied (Table 2). The CA treatments also registered significantly higher values of all SOC pools compared with CT in all the soil layers. The treatments PB and ZT had similar values of total SOC as well as its' different pools, in all the soil layers (Table 2). Among the nutrient management options, SSNM plots registered highest concentrations of VLSOC and LSOC in all the soil depths and were significantly higher than that of unfertilized control and FFP treatments. Although *Ad-hoc* nutrient management option had significantly lower VLSOC compared with SSNM in 0–7.5 cm soil depth, but had similar values of LSOC in all the soil depths. The NLSOC concentrations were also significantly higher under *Ad-hoc* and SSNM treatments, compared with that of unfertilized and FFP plots (Table 2). However, LLSOC was significantly higher under unfertilized treatment compared with that under SSNM, across the soil depths.

3.2. Soil organic carbon mineralization (C_t)

During the 90-day incubation period the cumulative SOC mineralization (C_t) dynamics at different temperatures (27, 32 and 37° C) are presented in Figs. 1–3 and Table 3. Tillage and nutrient management practices significantly affected the C_t values across soil depths (0–7.5, 7.5–15 and 15–30 cm). Overall SOC mineralization decreased with increasing soil depths irrespective of tillage and nutrient management treatments (Table 3). Irrespective of treatments and temperatures, higher proportion of total SOC mineralized from upper soil depths (Table 4). Across the tillage and nutrient management treatments, absolute C_t as well as the proportion of total SOC mineralized increased with increase in temperature at all sampling events (Figs. 1–3; Tables 3–4). The increase in ambient temperature (from 27 to 37° C) nearly doubled the percentage of SOC mineralised. A sudden increase in C_t was observed under PB and ZT plots from the 15th day onwards.

Irrespective of temperature regime, CT treatment had significantly lower C_t values throughout the incubation period than that of CA-based PB and ZT treatments. The PB treatment had significantly higher C_t across the incubation period, compared with ZT, from soils of 0–7.5 cm layer, whereas the opposite is true for the soils of lower depths (7.5–15 and 15–30 cm) (Figs. 1–3). In all the soil depths, the C_t values after 90 days incubation in CA-based PB/ZT were higher by 20.6–45.7% at 27° C, by 11.5–28.5% at 32° C and by 8.1–27.8% at 37° C compared with CT (Table 3). Except a couple of instances, ZT had significantly higher C_t compared with PB, after 90 days incubation. On the other hand, when the proportion of total SOC mineralized in 90 days period was concerned, the percentage SOC mineralized was similar from CT, PB and ZT from all soil depths at 32° C. The similar trends were followed from soils of 0–7.5 cm at 27° C, and from soils of 0–15 cm at 37° C

Table 2

Total soil organic carbon (SOC) and its different pools as affected by 5-years of tillage, residue and nutrient management in an Inceptisol.

Treatment	Total SOC (g kg ⁻¹ soil)			Very labile SOC (g kg ⁻¹ soil)			Labile SOC (g kg ⁻¹ soil)			Less labile SOC (g kg ⁻¹ soil)			Non-labile SOC (g kg ⁻¹ soil)		
	Soil depths (cm)														
	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30
<i>Tillage and residue management</i>															
CT	5.53 ^b	4.77 ^b	4.57 ^b	1.33 ^b	0.85 ^b	0.35 ^b	0.74 ^b	0.52 ^b	0.49 ^b	1.47 ^a	1.90 ^a	2.04 ^a	1.99 ^b	1.51 ^b	1.69 ^c
PB	6.90 ^a	5.75 ^a	5.27 ^a	1.53 ^a	1.08 ^a	0.50 ^a	1.06 ^a	0.81 ^a	0.67 ^a	1.32 ^b	1.59 ^b	1.81 ^b	2.99 ^a	2.27 ^a	2.28 ^b
ZT	6.75 ^a	5.82 ^a	5.44 ^a	1.43 ^{ab}	1.11 ^a	0.48 ^a	1.00 ^a	0.82 ^a	0.65 ^a	1.46 ^a	1.59 ^b	1.73 ^b	2.87 ^a	2.31 ^a	2.58 ^a
<i>Nutrient management</i>															
Unfertilized	5.49 ^b	5.01 ^b	4.49 ^b	1.22 ^d	0.84 ^b	0.22 ^d	0.81 ^b	0.66 ^b	0.50 ^b	1.66 ^a	1.75 ^a	1.97 ^a	1.80 ^c	1.75 ^b	1.79 ^b
<i>Ad-hoc</i>	7.13 ^a	5.84 ^a	5.52 ^a	1.50 ^b	1.12 ^a	0.50 ^b	1.09 ^a	0.80 ^a	0.70 ^a	1.40 ^b	1.69 ^a	1.87 ^a	3.14 ^a	2.23 ^a	2.44 ^a
FFP	5.69 ^b	4.95 ^b	4.65 ^b	1.33 ^c	0.81 ^b	0.31 ^c	0.72 ^b	0.53 ^c	0.51 ^b	1.38 ^b	1.81 ^a	1.97 ^a	2.26 ^b	1.80 ^b	1.86 ^b
SSNM	7.28 ^a	6.00 ^a	5.71 ^a	1.67 ^a	1.29 ^a	0.74 ^a	1.11 ^a	0.87 ^a	0.71 ^a	1.23 ^c	1.52 ^b	1.63 ^b	3.26 ^a	2.32 ^a	2.63 ^a

CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, *Ad-hoc*: recommended dose of fertilizers, FFP: Farmer fertilizer practices; SSNM: Site specific nutrient management. Means followed by a similar letter within a depth are not significantly different (at $P < 0.05$) according to least significant difference test.

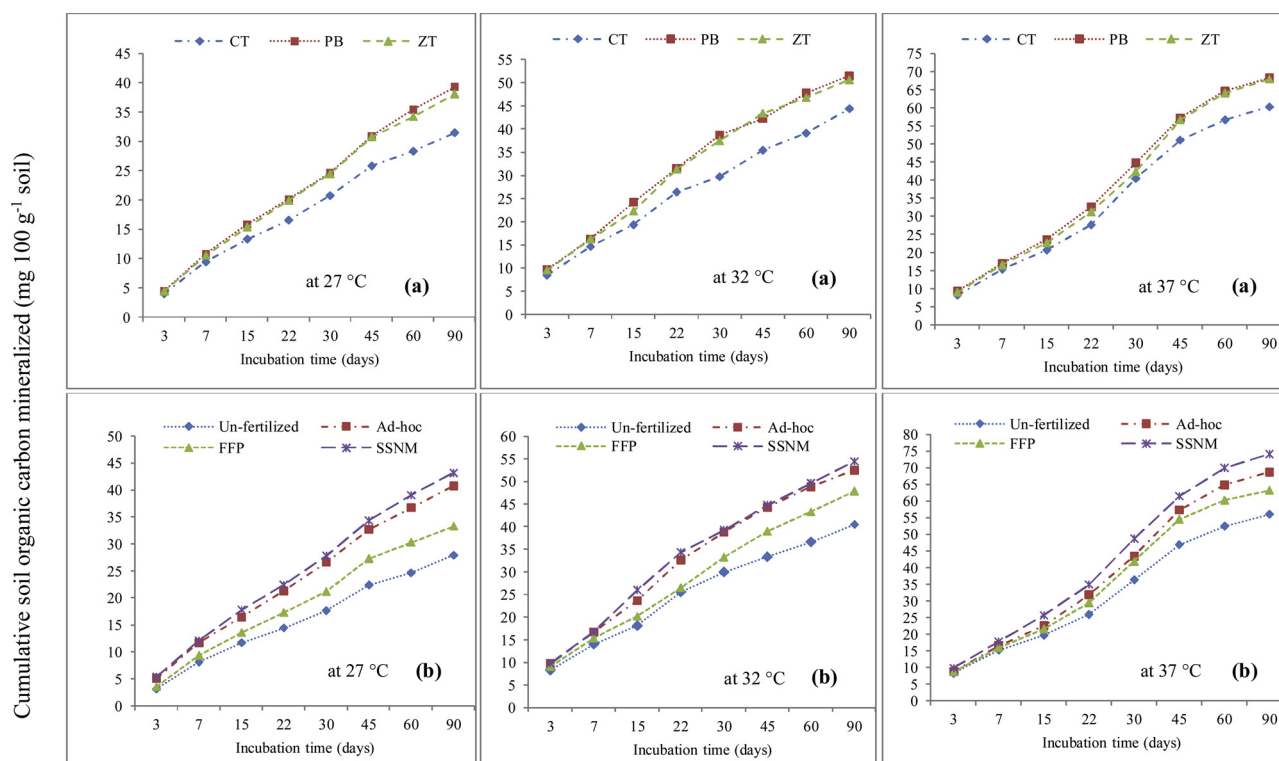


Fig. 1. Cumulative soil organic carbon mineralization as affected by 5-years of (a) tillage and residue management, and (b) nutrient management under maize-wheat-mungbean cropping system in an Inceptisol from 0 to 7.5 cm depth. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP: Farmers' fertilizer practices; SSNM: Site specific nutrient management.

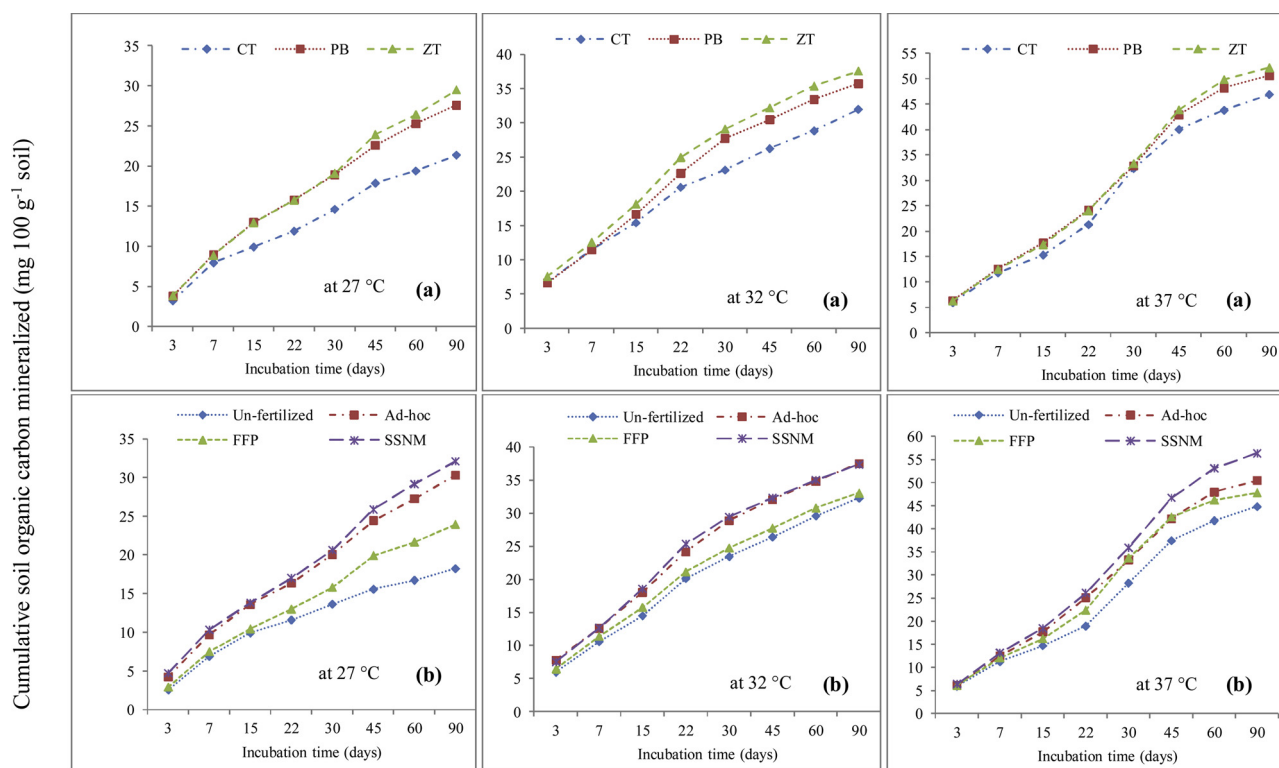


Fig. 2. Cumulative soil organic carbon mineralization as affected by 5-years of (a) tillage and residue management, and (b) nutrient management under maize-wheat-mungbean cropping system in an Inceptisol from 7.5 to 15 cm depth. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP: Farmers' fertilizer practices; SSNM: Site specific nutrient management.

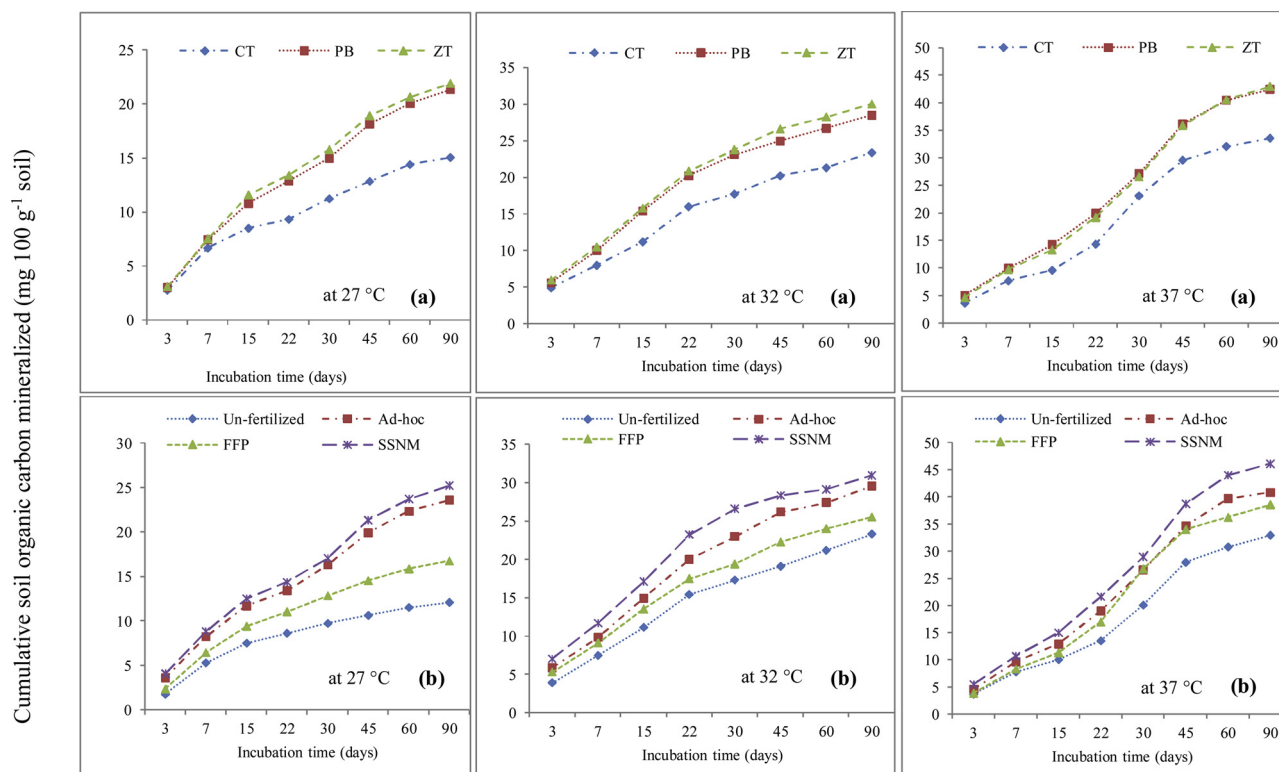


Fig. 3. Cumulative soil organic carbon mineralization as affected by 5-years of (a) tillage and residue management, and (b) nutrient management under maize-wheat-mungbean cropping system in an Inceptisol from 15 to 30 cm depth. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP: Farmers' fertilizer practices; SSNM: Site specific nutrient management.

(Table 4). At 27 °C, the percentage mineralization from lower soil depths (7.5–30 cm) were significantly ($P < 0.05$) higher under CA-based treatments (PB/ZT) compared with CT. Similar results were obtained from the soils of 15–30 cm layer at 37 °C. Across soil depths in all the tillage treatments the percentage of SOC mineralised ranged between 3.3–5.8% at 27 °C, 5.2–8.1% at 32 °C and 7.3–10.9% at 37 °C (Table 4).

Across the incubation period, the C_t was highest under SSNM, followed by Ad-hoc based nutrient management treatments. The C_t under SSNM and Ad-hoc were significantly higher compared with FFP, which was in-turn significantly higher compared with unfertilized control plots (Figs. 1–3). In most of the sampling events, SSNM registered significantly higher C_t compared with Ad-hoc; otherwise the difference in C_t values did not reach to the statistical significance level. The total C_t after 90 days incubation was highest under SSNM, followed by Ad-hoc,

FFP and unfertilized plots (Table 3), across the soil depths. All the nutrient management treatments had significantly different C_t values. On an average, the SSNM plots registered ~47%, 7% and 24% higher C_t values compared with unfertilized, Ad-hoc, and FFP plots (Table 3). Among different nutrient management options across the depths, SSNM (4.48–6.05%) has the highest percentage of total SOC mineralized at 27 °C, the values being at par with that under Ad-hoc treatments (Table 4). The percentage of total SOC mineralized at 27 °C under SSNM and Ad-hoc was often higher than that under FFP, which was in-turn significantly higher than unfertilized control plots. At higher temperatures, maximum proportion of total SOC mineralization occurred under FFP, the percentage values being either similar or higher than that of SSNM plots.

Table 3

Cumulative soil organic carbon mineralized (C_t) after 90 days from different layers as affected by 5-years of tillage, residue and nutrient management in an Inceptisol.

Treatment	C_t (mg 100 g ⁻¹) at 27 °C			C_t (mg 100 g ⁻¹) at 32 °C			C_t (mg 100 g ⁻¹) at 37 °C		
	Soil depths (cm)								
	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30
<i>Tillage and residue management</i>									
CT	31.5 ^c	21.4 ^c	15.1 ^c	44.5 ^b	32.1 ^c	23.5 ^c	60.3 ^c	46.8 ^c	33.5 ^c
PB	39.3 ^a	27.7 ^b	21.4 ^b	51.7 ^a	35.8 ^b	28.6 ^b	68.3 ^a	50.6 ^b	42.3 ^b
ZT	38.0 ^b	29.6 ^a	22.0 ^a	51.4 ^a	37.7 ^a	30.2 ^a	67.4 ^b	52.1 ^a	42.8 ^a
<i>Nutrient management</i>									
Unfertilized	27.8 ^d	18.3 ^d	12.1 ^d	41.5 ^d	32.4 ^c	23.4 ^d	55.4 ^d	44.8 ^d	32.9 ^d
Ad-hoc	40.8 ^b	30.4 ^b	23.7 ^b	52.7 ^b	37.7 ^a	29.7 ^b	68.6 ^b	50.4 ^b	40.8 ^b
FFP	33.3 ^c	24.0 ^c	16.8 ^c	48.0 ^c	33.2 ^b	25.6 ^c	63.2 ^c	47.7 ^c	38.5 ^c
SSNM	43.2 ^a	32.2 ^a	25.3 ^a	54.6 ^a	37.5 ^a	31.1 ^a	74.1 ^a	56.3 ^a	46.0 ^a

CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP: Farmers' fertilizer practices; SSNM: Site specific nutrient management. Means followed by a similar letter within a depth are not significantly different (at $P < 0.05$) according to least significant difference test.

Table 4

Proportion of total soil organic carbon (SOC) mineralized after 90 days from different layers as affected by tillage, residue and nutrient management.

Treatment	% Total SOC mineralized at 27 °C			% Total SOC mineralized at 32 °C			% Total SOC mineralized at 37 °C		
	Soil depths (cm)								
	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30
<i>Tillage and residue management</i>									
CT	5.66 ^a	4.42 ^c	3.26 ^b	8.06 ^a	6.72 ^a	5.19 ^a	10.86 ^a	9.76 ^a	7.27 ^b
PB	5.75 ^a	4.80 ^b	4.00 ^a	7.57 ^a	6.27 ^a	5.55 ^a	9.98 ^a	8.88 ^a	8.16 ^a
ZT	5.62 ^a	5.07 ^a	4.02 ^a	7.70 ^a	6.53 ^a	5.55 ^a	10.16 ^a	8.97 ^a	7.85 ^{ab}
<i>Nutrient management</i>									
Unfertilized	5.05 ^b	3.64 ^c	2.72 ^c	7.58 ^b	6.57 ^a	5.29 ^a	10.10 ^b	8.90 ^b	7.30 ^b
Ad-hoc	5.78 ^a	5.18 ^{ab}	4.26 ^a	7.53 ^b	6.49 ^a	5.38 ^a	9.79 ^b	8.72 ^b	7.39 ^b
FFP	5.84 ^a	4.85 ^b	3.57 ^b	8.43 ^a	6.73 ^a	5.52 ^a	11.11 ^a	9.65 ^a	8.24 ^a
SSNM	6.05 ^a	5.38 ^a	4.48 ^a	7.54 ^b	6.24 ^a	5.53 ^a	10.34 ^b	9.54 ^a	8.12 ^a

CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP: Farmers' fertilizer practices; SSNM: Site specific nutrient management. Means followed by a similar letter within a depth are not significantly different (at $P < 0.05$) according to least significant difference test.

3.3. Decay rates (K_c) of soil organic carbon mineralization

The decay rates (K_c) of SOC mineralization varied significantly among tillage, residue and nutrient management options (Table 5). In general, higher K_c values were observed at higher temperature across the soil depths, in all the treatments. Interestingly, at 27 °C, the K_c decreased with increasing soil depth, whereas, at higher temperature (32 °C and 37 °C) reverse trends were observed (Table 5). Among different tillage and residue management options, the highest K_c at 27 °C was observed under PB, while at 37 °C the K_c values were highest under CT. Among the CA treatments, almost always, the PB registered significantly higher K_c compared with ZT. In general, the K_c under fertilized plots was significantly higher than that under unfertilized plots in 27 and 32 °C, whereas, the reverse trend was observed at 37 °C (Table 5). At 27 °C, the K_c under SSNM was significantly higher as compared with FFP and Ad-hoc from surface soils of 0–7.5 cm layer, whereas in lower depths the values were similar or lesser. At 37 °C, all the fertilized plots had similar K_c values irrespective of soil depths, except in one instance (Table 5).

3.4. Temperature sensitivity (Q_{10}) of soil organic carbon mineralization

The Q_{10} is a potential measure of temperature sensitivity of SOC mineralisation. Irrespective of tillage, residue and nutrient management options the SOC in lower soil depths (7.5–15 and 15–30 cm) is ~1.3 and 2.1 times more temperature sensitive respectively than surface soil depth of 0–7.5 cm soil depth (Table 5). The Q_{10} differed significantly ($P < 0.05$) among the tillage and residue management treatments

across soil depths except in 0–7.5 cm (Table 5). The Q_{10} was highest under CT at sub surface (7.5–15 and 15–30 cm) soil depths, and were significantly higher compared with that under ZT. Under CT treatment the SOC was 1.1–1.3 and 1.4–1.5 times more sensitive to temperature rise compared with CA-based PB and ZT in 7.5–15 cm and 15–30 cm soil layer, respectively (Table 5). Among the nutrient management options, SOC in unfertilized control plots was 1.2–1.8, 1.1–2.2 and 1.1–2.3 time more temperature-sensitive than FFP, Ad-hoc and SSNM based nutrient managed plots, respectively. The Q_{10} were similar in all the fertilized plots in 0–15 cm soil depth, whereas in 15–30 cm, significantly higher values were obtained under FFP compared with Ad-hoc and SSNM plots.

4. Discussion

4.1. Impact of tillage and residue management on dynamics of soil organic carbon

The results of the present study showed that adoption of ZT/PB with residue retention significantly ($P < 0.05$) improved total SOC as well as VLSOC and LSOC as compared with CT with residue incorporation. In an array of global scientific literature, the intensive tillage has been reported to deplete SOC to a great extent (Dey et al., 2018). These losses of SOC can be mitigated by eliminating tillage, retention of vegetative soil cover or through addition of crop residue to soil (Lal, 2007). Mohanty et al. (2015) observed tillage reduction in association with residue retention increased the total SOC by approximately 20% over conventional systems in alluvial soils of India. Yaduvanshi and Sharma

Table 5Decay rate ($K_c \times 10^{-2}$) and temperature sensitivity (Q_{10}) of SOC mineralization from different layers as affected by 5-years of tillage, residue and nutrient management in an Inceptisol.

Treatment	$K_c \times 10^{-2}$ (day ⁻¹) at 27 °C			$K_c \times 10^{-2}$ (day ⁻¹) at 32 °C			$K_c \times 10^{-2}$ (day ⁻¹) at 37 °C			Q_{10}		
	Soil depths (cm)											
	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30
<i>Tillage and residue management</i>												
CT	2.30 ^b	2.21 ^b	1.84 ^b	3.26 ^b	3.57 ^c	3.84 ^b	3.58 ^a	4.91 ^a	7.34 ^a	1.56 ^a	2.25 ^a	4.03 ^a
PB	2.37 ^a	2.30 ^a	2.14 ^a	3.50 ^a	3.78 ^b	4.70 ^a	3.51 ^a	4.38 ^b	5.29 ^b	1.49 ^a	1.97 ^{ab}	2.63 ^b
ZT	2.22 ^c	2.13 ^c	1.84 ^b	3.54 ^a	4.08 ^a	4.48 ^a	3.38 ^b	3.77 ^c	4.99 ^b	1.54 ^a	1.80 ^b	2.82 ^b
<i>Nutrient management</i>												
Unfertilized	2.33 ^b	1.94 ^c	1.59 ^b	3.09 ^c	3.39 ^a	3.43 ^c	3.85 ^a	5.58 ^a	7.85 ^a	1.66 ^a	2.88 ^a	4.89 ^a
Ad-hoc	2.18 ^c	2.38 ^a	2.07 ^a	3.66 ^b	4.05 ^a	4.19 ^b	3.39 ^b	3.99 ^b	4.46 ^b	1.56 ^{ab}	1.68 ^b	2.23 ^c
FFP	2.32 ^b	2.38 ^a	2.01 ^a	3.04 ^c	3.85 ^b	4.25 ^b	3.32 ^b	3.79 ^b	6.72 ^a	1.44 ^b	1.59 ^b	3.36 ^b
SSNM	2.35 ^a	2.16 ^b	2.08 ^a	3.94 ^a	3.95 ^{ab}	5.49 ^a	3.40 ^b	4.05 ^b	4.47 ^b	1.45 ^b	1.88 ^b	2.15 ^c

CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP: Farmers' fertilizer practices; SSNM: Site specific nutrient management. Means followed by a similar letter within a depth are not significantly different (at $P < 0.05$) according to least significant difference test.

(2008) reported significant increase in SOC under ZT plots (3.17 g kg^{-1}) compared with conventional plots (2.84 g kg^{-1}) in an alluvial soil of NW-IGP under RW system. Surface-retained residues under ZT/PB decomposed more slowly than soil-incorporated residues in CT, because of reduced availability of nutrients to microbes colonising the surface residue. Ploughing incorporated residues into a larger volume of soil and therefore increased the SOM decomposition, by increasing the contact between soil microorganisms and crop residues and by SOM disruption (Dey et al., 2018). Thus surface-retained residues under ZT/PB plots provided steady source of SOC to the soil due to their slower decomposition, and also protect the soil from raindrop impact (Dikgatlhe et al., 2014). All these processes resulted in attainment of higher SOC under ZT/PB plots compared with CT (Table 2). The carbon pool index (CPI), which is indicative of build-up of total SOC over initial values, was reported significantly higher under ZT/PB compared with CT (Fig. 5).

Alike total SOC, different SOC pools of varying lability was significantly higher under PB/ZT treatments with residue retention, compared with CT with residue incorporation (Table 2). As reported in earlier literature (Bhattacharyya et al., 2012) we also found significant improvement in labile SOC pools upon practising PB/ZT in lieu of CT. The tillage reduction manifested beneficial effects on recalcitrant pools also in our study (Table 2). The differential tillage and residue management had interesting effects on lability of SOC. The annual residue inputs were constant in all the experimental plots over the years ($\sim 5\text{--}7.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$), and acted as a continuous source of labile SOC. But, due to incorporation practices in CT, the mean residence time of SOC were lower in these plots. On the other hand under PB/ZT plots, the C input improved the intra-aggregate C content by virtue of improved aggregation under minimum mechanical disturbances (Six et al., 2002a, 2002b). The formation of microaggregates inside macroaggregates provided enhanced physical protection towards SOC against mineralisation (Six et al., 2000). Thus, SOC developed better recalcitrance under PB/ZT which is evident by the significantly lower C lability values under these treatments compared with CT (Fig. 4). Minimal disturbances under PB/ZT ensured lower lability of SOC as compared to initial C lability, while residue incorporation under CT registered higher lability compared with initial values. As a result, we obtained significantly lower values of lability index (LI) under PB/ZT compared with CT plots (Fig. 5). Under PB, the tillage reduction had maximum effects on surface (0–7.5 cm) layer, with $\text{LI} < 1$, signifying loss of lability compared to initial. Whereas in lower layers, the values of $\text{LI} \sim 1$, which indicates similar recalcitrance as of the initial SOC (Fig. 5). The contrasting trends of LI and CPI culminated in non-significant variation of CMI due to differential tillage and residue management options for 5-years (Fig. 5).

Lesser microbial activity, combined with lower nutrient and SOC content in lower soil depths also contributed to the decrease in C_t with increasing soil depths (Tisdall and Oades, 1982). As the total SOC was

higher under PB/ZT (Table 2), cumulative SOC mineralization was also higher under these CA-based treatments, compared with CT (Table 3). Higher substrate availability for microbes under PB and ZT resulted into higher C_t in these treatments (Kumar et al., 2018). The calculated K_c was higher under PB at 27 and 32 °C compared with CT, whereas the reverse trend was observed in elevated temperature (37 °C) (Table 5). Greater availability of very labile and labile SOC to microbes under CA-based treatments might be a reason for this phenomenon. On the other hand, at higher temperatures, previously unavailable LLSOC became available substrate for microbial decomposition. Thus, higher content of LLSOC in CT compared with PB (Table 2), justifies the higher K_c values in CT plots at elevated temperature (37 °C).

4.2. Impact of nutrient management on dynamics of soil organic carbon

The NE-based nutrient application under SSNM plots advocated balanced supply of nutrients synchronising the crop nutrient demand (Pampolino et al., 2012). Balanced nutrient application enhanced crop shoot and root biomass (Pooniya et al., 2015), which in-turn ensured higher rate of residue addition under SSNM compared with unfertilized and FFP plots under conventional and ZT condition in both flat and permanent raised beds. Enhanced rate of annual C-input along with balanced nutrition affected stabilization of SOC by virtue of enhancement of residue quality and alteration of microbial activity, diversity, and C use efficiency. Balanced basal NPK application helped in initial root proliferation, which later contributed to SOC, in terms of rhizodeposition as well as root biomass C. Aula et al. (2016) reported significant improvement in surface SOC in response to annual application of 134 kg N ha^{-1} . Pooniya et al. (2015) reported $\sim 8\%$ higher WBC under NE-based nutrient application compared with unfertilized control plots. Incorporation/retention of crop residues, of leguminous (mungbean) and non-leguminous (maize and wheat) origin provided SOM of varying decomposability, ranging from resistant lignin to easily decomposable carbohydrates. These significantly enhanced SOC pools of different lability (Table 2).

Balanced nutrient applications under SSNM were synchronous to crop nutrient demands, resulted in higher biomass and in-turn higher amount of annual C input. The unfertilized plots registered significantly higher lability of SOC as compared with SSNM and other plots with fertilization practices (Fig. 4). The SOC under 5-years of cultivation without fertilizer application gained considerable lability compared with initial, the effect being prominent in the surface 0–7.5 cm soil layer. On the other hand, the C lability decreased under fertilized plots, compared to initial, as evident by $\text{LI} < 1$ in these plots (Fig. 5). Significant higher CPI under SSNM compared with unfertilized plots also substantiates this phenomenon (Fig. 5). The findings of Singh and Benbi (2018) corroborates with our results. But when we consider the effect of nutrient management on individual labile SOC pools viz., VLSOC, LSOC and LLSOC, a contrasting scenario emerged. Whilst the VLSOC and

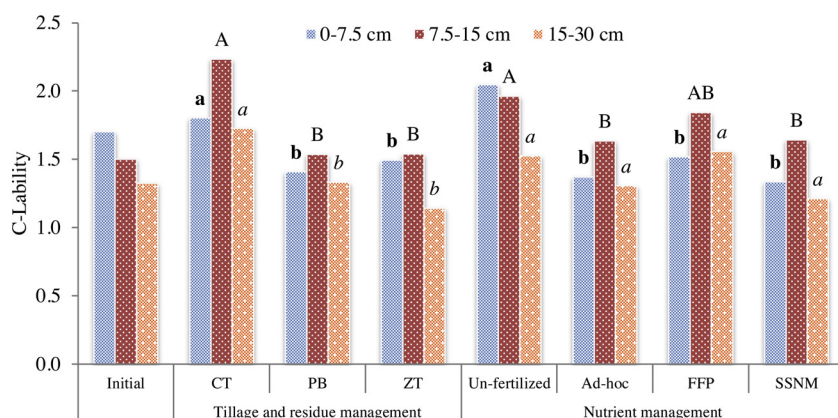


Fig. 4. Effect of different tillage, residue and nutrient management on soil organic carbon lability after five years of continuous cultivation. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP: Farmers' fertilizer practices; SSNM: Site specific nutrient management. Means followed by a similar letter within a depth are not significantly different (at $P < 0.05$) according to least significant difference test.

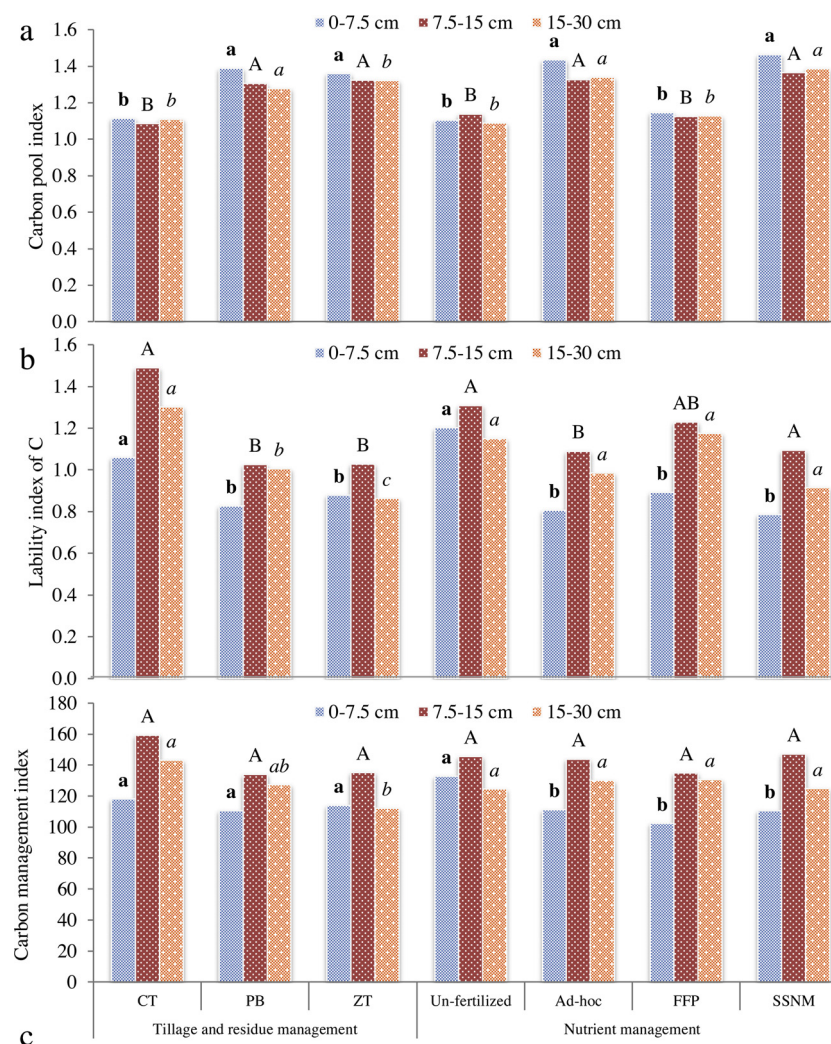


Fig. 5. Effect of different tillage, residue and nutrient management on (a) Carbon pool index, (b) Lability index of carbon and (c) Carbon management index after five years of continuous cultivation. CT: Conventional tillage, PB: Permanent bed, ZT: Zero tillage, Ad-hoc: recommended dose of fertilizers, FFP: Farmers' fertilizer practices; SSNM: Site specific nutrient management. Means followed by a similar letter within a depth are not significantly different (at $P < 0.05$) according to least significant difference test.

LSOC were significantly higher under SSNM compared with unfertilized plots, an opposite trend was found for LLSOC (Table 2). The application of inorganic fertilisers might have slowed down formation of particulate organic matters (POM) and subsequent encrustations of fine POM with clay particles. This in-turn inhibits the formation of stable microaggregates within macroaggregates, and is reflected on significant lower values of LLSOC under SSNM compared with unfertilized plots (Table 2) (Liang et al., 2014).

The C_t was found significantly higher under SSNM, compared with no or imbalanced use of fertilizers for a period of 5-years (Table 3). A significant higher C-input under these plots ensured higher substrate availability for soil microbes, which in-turn reflected in higher values of SOC (Aula et al., 2016; Pooniya et al., 2015), and soil respiration or SOC mineralization (Table 3). At 27 and 32 °C, K_c was significantly higher under SSNM compared with unfertilized plots, whereas the trend completely reversed at 37 °C (Table 5). At lower temperature regimes (27 and 32 °C), SOC mineralization mainly occurred from VLSOC and LSOC, whereas at elevated temperature (37 °C), LLSOC was the main contributor towards C_t . The significant higher values of VLSOC, LSOC under SSNM compared with unfertilized plot, and a complete reverse trend of LLSOC substantiates this contention (Table 2).

4.3. Temperature sensitivity of soil organic carbon mineralization

Generally, an increase in ambient temperature increased mineralization (Figs. 1–3, Tables 3–4) and decay rates of SOC (Table 5). Apparent temperature sensitivity of SOC mineralization depends on biophysical and biochemical factors. Higher temperature enhances dissolution and diffusion of C substrates towards active sites of enzymes. Thus, substrate availability towards microbial decomposition enhances (Xu and Saiers, 2010; Davidson et al., 2012). Desorption of otherwise recalcitrant SOM–humate complexes were also favoured at elevated temperatures (Davidson and Janssens, 2006). These phenomena invariably reduce physical protection and accelerate SOM decomposition (Conant et al., 2011; Schmidt et al., 2011). Elevations of temperature often successfully solubilize waxes and lipids from the cell-membranes of dead microbes, which were otherwise resistant to degradation normally (Davidson and Janssens, 2006). The Q_{10} values signify temperature sensitivity of SOC decomposition. We obtained higher Q_{10} values in the lower layers of soil (Table 5). Decreasing substrate quality (i.e. degree of resistance to microbial attack) with soil depth might be responsible for the rise in Q_{10} values in sub-surface soils (Fierer et al., 2003; Karhu et al., 2010). Another possible explanation for higher Q_{10} values in the sub-surface soil than in the top soil may be the variations in microbial community structure and metabolic

activities between these two soil layers, but this needs verification from more experimental evidences.

The extent of increment of K_c with an elevation of temperature was much higher under CT compared with PB/ZT (Table 5), irrespective of soil depth. Greater physical protection of SOC under PB/ZT restricted their availability towards microbial degradation (Six et al., 2002b). The reduced pore size under CA-based practices also counteracted the enhancement of SOC decay under elevated temperature (Pulleman and Marinissen, 2004). As a result we obtained lower Q_{10} values under PB/ZT compared with CT, although there was no significant variation in Q_{10} from surface 0–7.5 cm soil layer (Table 5). On the other hand, significantly lower Q_{10} was obtained under SSNM compared with unfertilized plots from all soil depths (Table 5). It implied the SOC under SSNM plots or under PB/ZT plots were less prone to loss under a sudden elevation of ambient temperature. The higher C input behaved as an energy barrier to SOM decay. Among the potentially mineralizable SOC pools, the LLSOC required highest activation energy, which can be overcome under elevated temperature conditions. Thus, the treatments having higher values of LLSOC (CT and unfertilized) also displayed higher sensitivity to elevated temperature (Q_{10}) as compared with treatments having lower LLSOC (PB/ZT and SSNM), among different tillage, residue and nutrient management practices (Tables 2 and 5). Conant et al. (2011) also reported that decomposition of recalcitrant substrate requiring high activation energy will increase with increasing temperatures compared to those of labile substrates with low activation energy.

The higher Q_{10} of sub-surface soils under CT compared with PB/ZT conveys the threat of increased C loss from comparatively less labile SOC pools of lower soil depths in the global warming scenarios of near future. It is a fact that more than half of SOC is stored in sub-surface soils in this site (Ghosh et al., 2016) and the entire soil profile is anticipated to experience the comparable extent of warming (but different diurnal and seasonal changes). There is an earnest need to research the susceptibility of subsurface soil carbon to ecological change in future investigations and kinetic studies.

5. Conclusions

In accordance with the first hypothesis, CA practices along with precision nutrient management significantly impacted SOC build-up. The improvements were higher in non-labile SOC as compared to labile SOC pools, thus stabilizing C in these practices. Our incubation study mimicking a single crop season showed C mineralization mostly from very labile, labile and less labile SOC. Among the different pools, the less labile SOC was most sensitive to elevated temperature, thus making it the most important SOC pool in view of global temperature change scenario. We stand in a fear of C loss in near future, from a pool of less lability which is otherwise stable in current temperature scenario. Thus the practices which encourage the build-up of non-labile SOC or recalcitrant SOC should be promoted. The Q_{10} values in CA and SSNM-based plots were lower than conventional plots. Thus, the second hypothesis was accepted. The PB/ZT or SSNM plots had considerable potential in having less proportional (to its total SOC) SOC decomposition under increased temperatures. Thus, among all practices, SSNM based CA plots not only had highest SOC accumulation, but also could have less SOC losses under elevated temperatures and hence should be recommended.

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